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## SUMMARY

Fast-response thermometry and high-speed motion pictures were employed in a study of the transient-heating mechanisms that take place as nucleate boiling develops on a horizontal surface.

Evidence of free convection as well as thermal diffusion was observed. For subcooled conditions, an overshoot and a significant undershoot in surface temperature occurs near the end of the transient. The latter coincided with the development of a large vapor mass on the surface. Transient thermal-layer growth histories, measured with shadowgraphs, are reported for water, and the dependence of thermal-layer thickness on bulk temperature is shown. The transient-boiling data are discussed in terms of their relation to the hysteresis phenomenon noted in steady-state nucleate boiling. Surface condition (number of nucleation sites) and gravity effects on the transient boiling process are discussed.

## INTRODUCTION

Developments in the technology of power generation and propulsion have sponsored considerable interest in a more thorough understanding of boiling heat transfer. A sizable international research effort is being directed toward boiling and two-phase flow.

In particular, there is interest in the transient behavior of boiling because the control and response of some thermal systems depend to a considerable degree on the transient characteristics of boiling. A limited amount of literature on transient boiling is available (ref. 1 to 4). Perhaps the most comprehensive treatment has been done by Johnson et al. (refs. 3 and 4). Various exponential transient times, including a step function, were studied by these researchers.

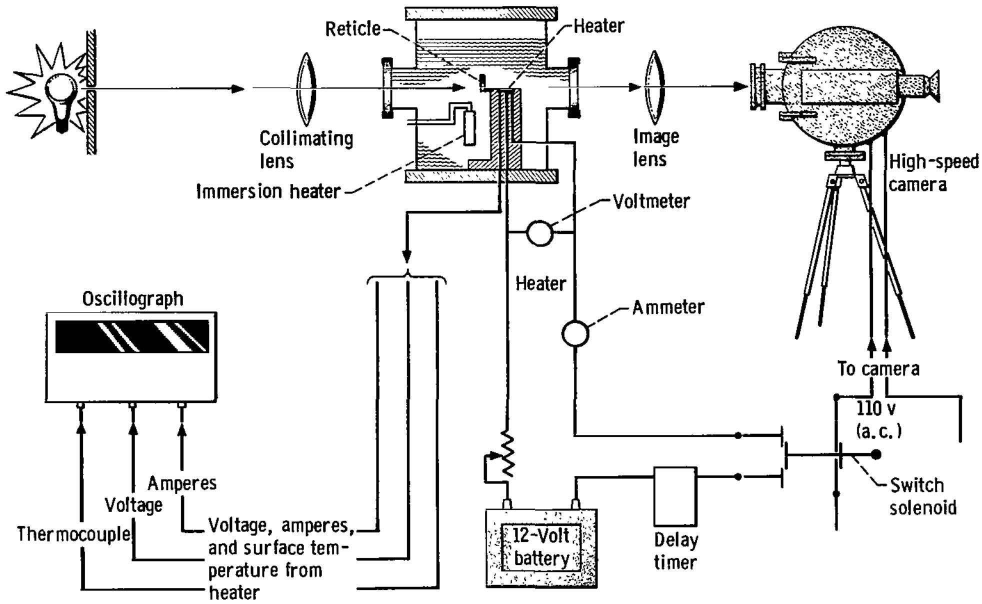
Besides producing response time information on boiling, transient studies have given new insight into the mechanism of boiling. Discussions in the transient-boiling literature cited attest to the value of this kind of experimentation. Observations of time and thermal-history dependence in establishing steady-state boiling conditions (refs. 5 and 6) turned the author's attention to the transient problem. Even within the nucleate portion of the boiling curve, a hysteresis loop was observed, which illustrated the sensitivity to the manner of approaching the steady-state operating point.

The object of this research program was to study the mechanism of transient nucleate boiling on a horizontal surface and to compare this with the vertical surface already studied (ref. 4). The thermal history of a thin horizontal surface was studied using two fluids of contrasting properties (alcohol and water). The bulk temperature of the fluids was varied to produce a range of subcoolings. Various levels of step inputs to the heater were introduced. High-speed photography was employed to record the transient heating phenomenon and to record shadowgraph images of the thermal layer during the transient. The heat transport mechanisms associated with the transient are discussed and compared, where possible, with analytical treatment. Thermal-layer growth histories for water on both horizontal and vertical surfaces are presented. The effects of body force and surface condition on the development of the thermal layer and the onset of boiling are discussed. Finally, these transient findings are discussed in terms of existing models of nucleate-boiling heat transfer, and explanations for the steady-state boiling hysteresis phenomena are offered.

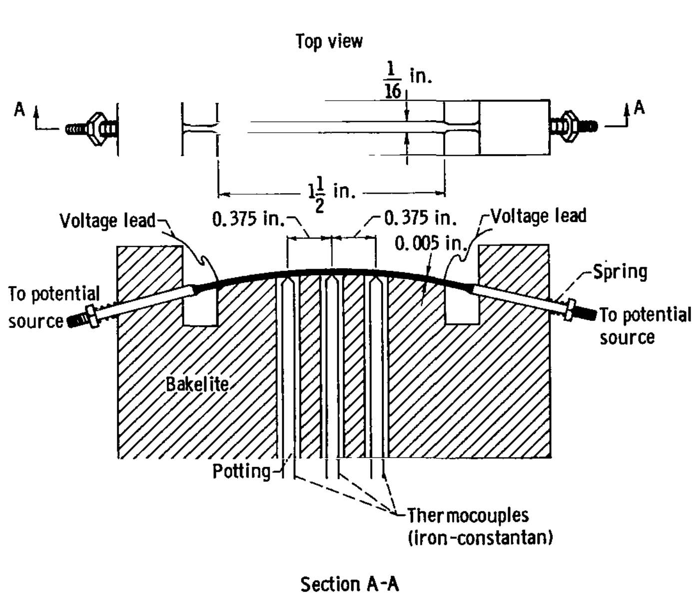
## APPARATUS AND PROCEDURE

The general setup of the apparatus is shown in figure 1(a). In the actual execution of the program, however, the experimentation was divided into two phases. In phase I, transient heat-transfer data and high-speed motion pictures were gathered for water and alcohol boiling above a horizontal heater strip. In phase II, only water was studied and both horizontal and vertical heaters were employed, the vertical-heater data being used for comparative purposes. No transient heater-strip temperatures were recorded for the vertical orientation. High-speed motion pictures of shadowgraph images of the thermal layer were recorded. The motion pictures gave a growth history of the thermal layer during the transient for both the horizontal and the vertical orientations.

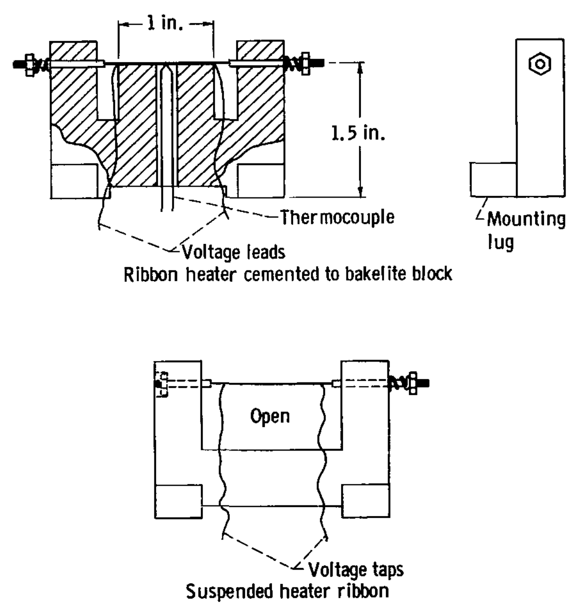
Figure 1(b) shows the test section and included instrumentation used in phase I. The test section included a Chromel strip or ribbon ($1\frac{1}{2}$ in. long by 1/16 in. wide by 0.005 in. thick) cemented to a bakelite block. As is shown in figure 1, three thermocouples were attached to the underside of the Chromel strip to measure the surface temperature. These couples were not located at the boiling surface, but it was considered important not to disturb the boiling surface with thermocouple attachment. The couples were only 0.005 inch away from the real boiling surface, so the temperature they sensed was close to that of the surface temperature. There was some time lag between the actual surface temperature and the temperature sensed by the couple. This delay was estimated




(a) General setup.




(b) Test-section configuration used in phase I. (Not to scale.)




(c) Test sections used in phase II.

Figure 1. - Apparatus and instrumentation.

to be approximately 1 millisecond from a transient conduction solution, which is small compared to the overall boiling transient.

Figure 1(c) shows the two types of test sections employed in phase II. The same Chromel ribbon was used to make these heaters as was used to make those in phase I; however, the heater length was shorter. One heater ribbon was cemented to a Bakelite block; the other ribbon was suspended across a yoke so that the heater could be exposed to liquid on both sides. As is shown in figure 1(c), the cemented ribbon has a thermocouple in the center to measure surface temperature. The suspended ribbon has no thermocouple; it was used for photographic purposes only. Both test-section configurations were equipped with voltage taps so that the electrical power dissipated in the heater could be measured. A standard 12-volt automotive wet-cell battery was used as the power source. The output from the battery was regulated by coarse- and fine-adjustment variable resistors. For phase I, a fast-acting double-throw switch was used to apply power to the heater ribbon. This switch permitted change in the polarity across the heater so that the electrical potential sensed by the thermocouples could be measured. By reading the thermocouples for both polarities, the direct-current pickup at steady-state conditions could be cancelled out by simply averaging the readings.

The general operating procedures for phases I and II were almost identical. The heater tank was filled with either degassed distilled water or with laboratory-pure methyl alcohol. By means of immersion heaters, the bulk temperature was set at a prescribed level. A common time-trace reference was introduced into the high-speed motion-picture camera and into the oscillograph, which recorded the transient levels of surface temperature and electrical power. The precision of synchronization for the common time traces was adequate. This trace was activated when the power switch was thrown.

The power-level rheostats were preset and the fast-acting power switch was thrown. Approximately 1 second before the power went on, the camera and oscillograph were started so that they would be up to speed when the heating transient began. The heater remained on until a considerable period of steady-state heating was observed. This procedure was repeated for several bulk temperatures and over a range of heat fluxes.

For phase II, the shadowgraph optics made the adjustment of lighting and camera positioning more difficult. A precision reticle was inserted into the pool so that the thickness of the thermal layer could be determined from the picture.

## RESULTS AND DISCUSSION

Figures 2 and 3 are transient surface temperature traces for alcohol and water, respectively, taken during phase I. Various levels of subcooling for 1 atmosphere of pressure are represented in these figures.

In general, these transient traces for horizontal surfaces resemble those presented in references 3 and 4 for vertical surfaces. Reference 4 represents

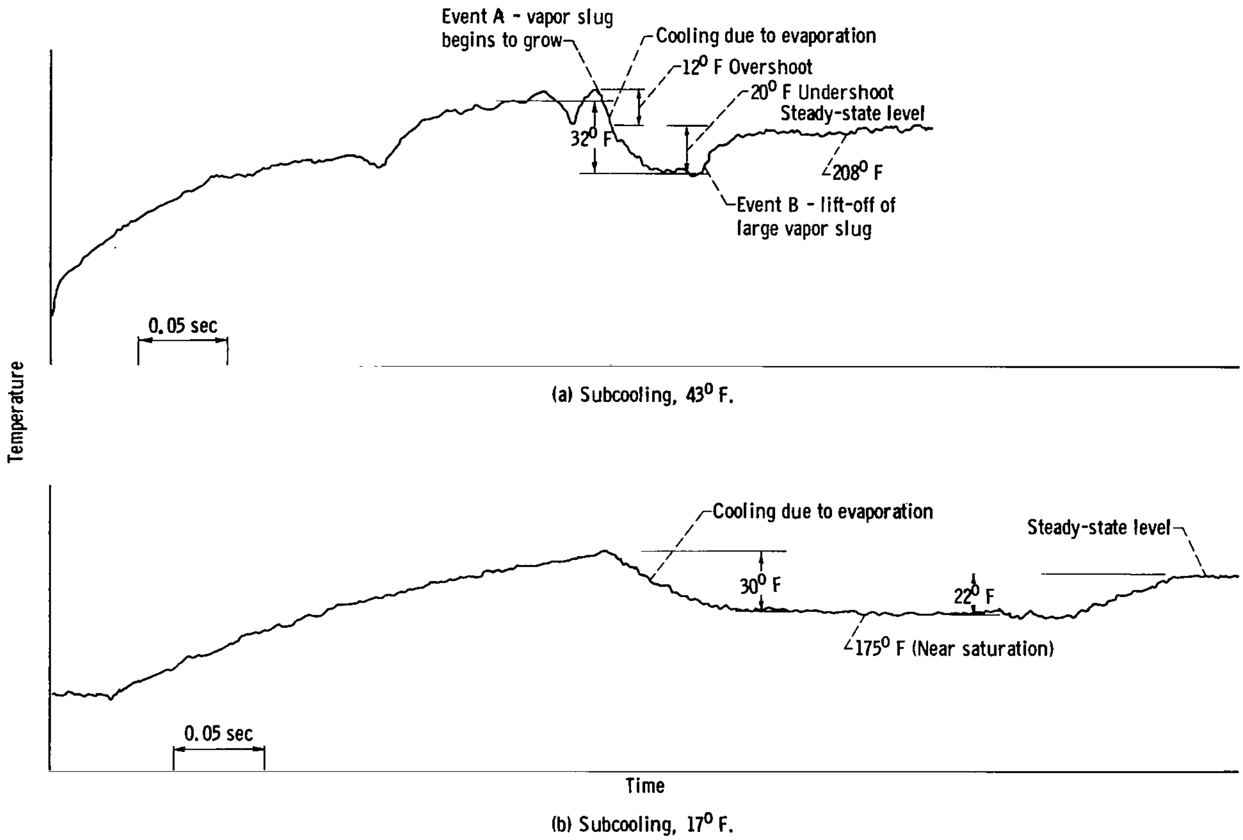
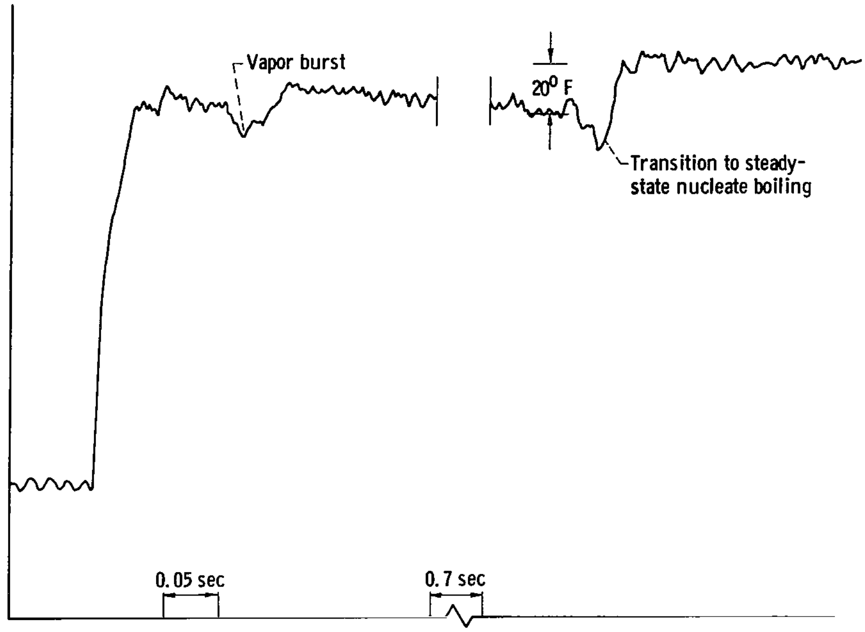
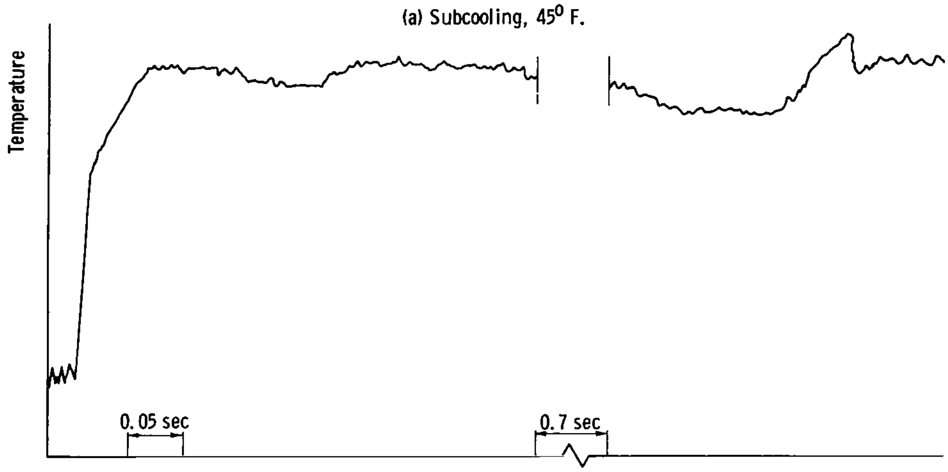



Figure 2. - Transient surface temperature traces for alcohol. Saturation temperature, 173° F. Pressure, 1 atmosphere.

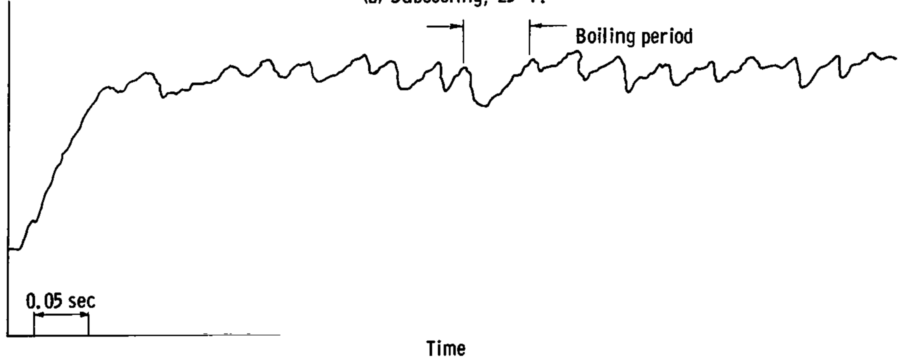
the more comparable case because the heating was also a step increase; in reference 3 the heating was by ramp of varying duration. A definite wall-temperature overshoot, as defined in reference 3, does exist (see fig. 2(a)). In the transient traces taken for subcooled water, the overshoot and undershoot temperature traces were harder to discern. (It should be noted that figs. 2 and 3 are not to the same scale.) The cooling effect of large vapor bursts was apparent (fig. 3(a)). The vapor bursts with water did not appear as large in volume as those with alcohol. Perhaps this could be accounted for by the higher heat of vaporization of water. In the highly subcooled cases, an especially sudden drop in surface temperature follows the overshoot. The sudden drop in surface temperature for highly subcooled alcohol is noticeable in figure 2(a). Figure 2(a) is marked with the coincident data obtained from the high-speed motion pictures. At the peak of the wall-temperature overshoot, a large slug of vapor developed and grew very quickly. Figure 4 is a series of prints of the high-speed frames taken during the growth of the alcohol vapor slug. These slugs were present for both water and alcohol, although a larger volume of vapor appeared with alcohol. Coincident with the growth of vapor is the rapid cooling of the wall temperature (see fig. 2(a) between events A and B). This rapid cooling is attributed to near-surface evaporation as evidenced in the production of the large quantities of vapor. Several reports (refs. 7, 8, and 9) have shown that evaporation is a very significant factor in establishing the heat-flux level associated with nucleate boiling.




(a) Subcooling, 45° F.




(b) Subcooling, 23° F.




(c) Subcooling, 6° F.

Figure 3. - Transient surface temperature traces with subcooled water. Pressure, 1 atmosphere.

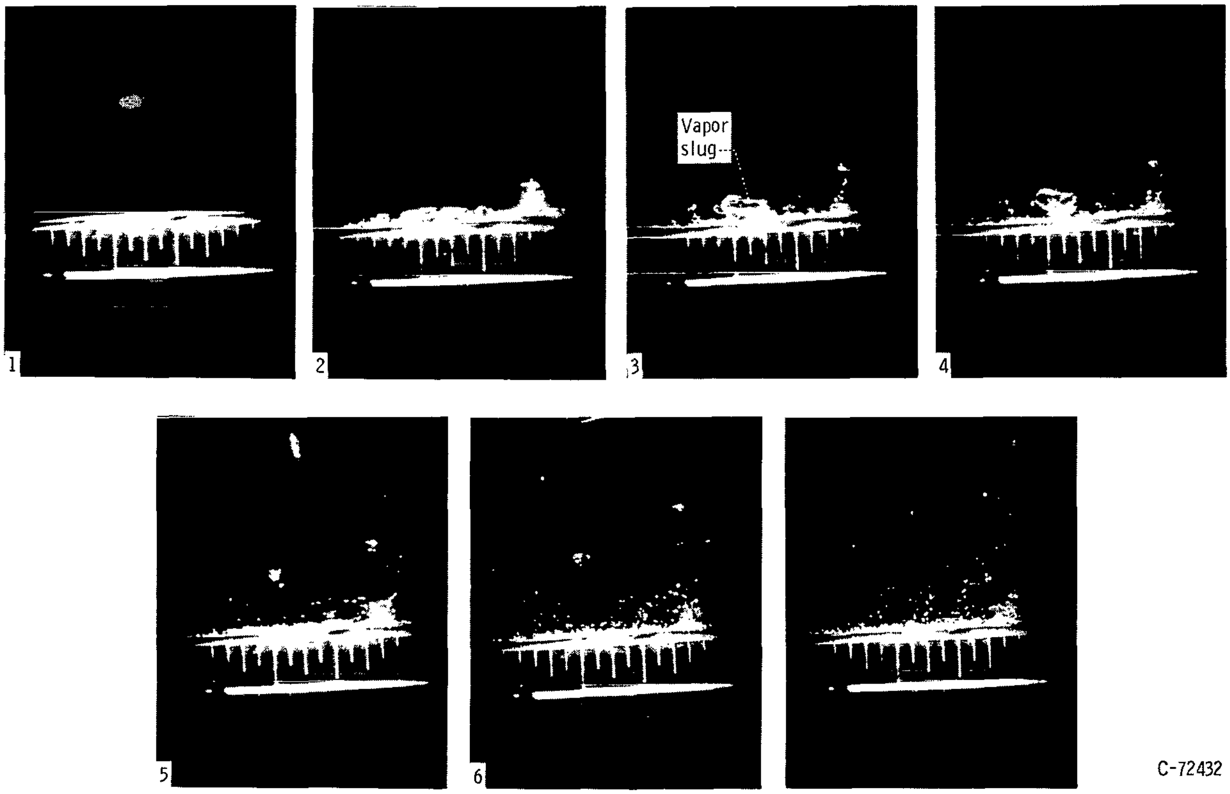
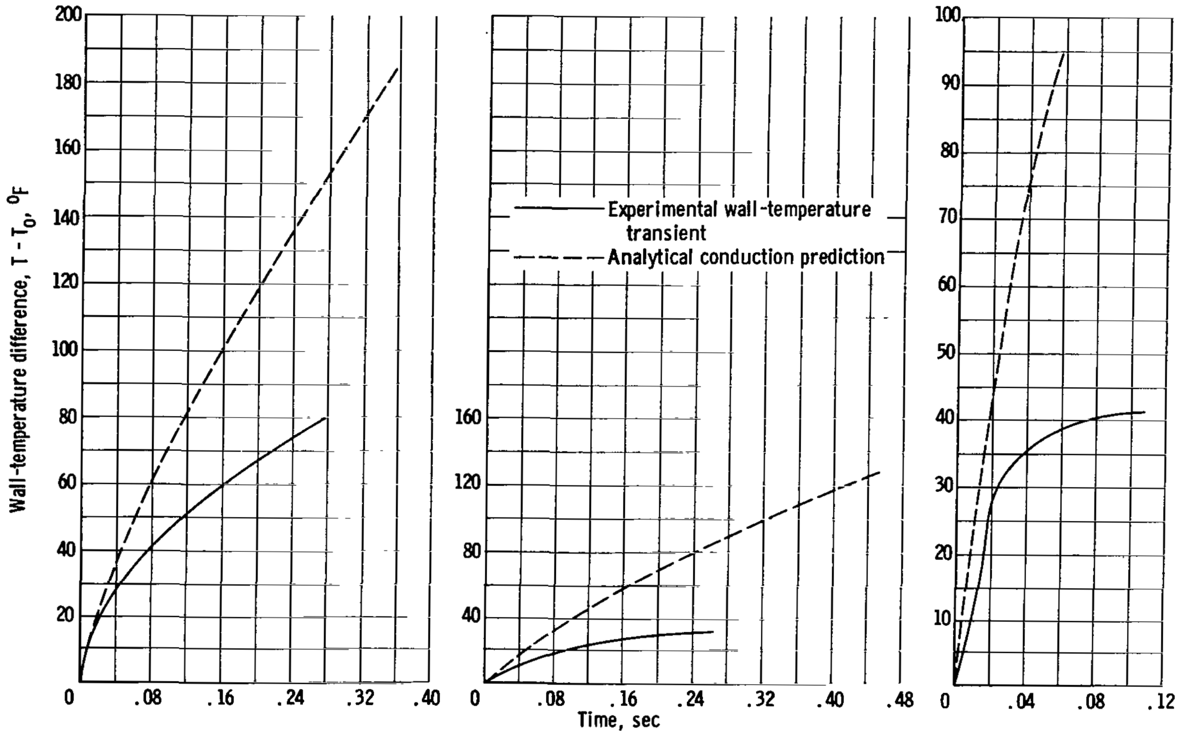



Figure 4. - Sequence showing rise of vapor slug and transition into nucleate boiling. Fluid, alcohol; total time, ~0.5 second.

In reference 10, the rate of vapor production from a surface that is instantaneously heated to the boiling temperature was computed to be proportional to the square root of time. It is interesting to observe in figure 2(a) that surface temperature between events A and B decays as a square root function of time. Assuming that the heat of vaporization is the cooling mechanism signifies that the mass of vapor produced is proportional to the square root of time (which is in agreement with ref. 10). Apparently this transient burst of vapor is important in thermally stabilizing the heater for the onset of steady nucleate boiling. For example, in figure 2(a) steady nucleate boiling follows the rapid development and rise of the vapor slug. Although it cannot be proven experimentally, it is speculated that the vapor slug emanates from a very limited number of sites before the thermal layer reaches a generally stabilized condition that will support boiling at many sites. The vapor slug seems to develop explosively as in some cavitation phenomenon.

As was mentioned previously, the collection of transient traces in figures 2 and 3 shows that this sudden cooling after the surface temperature overshoot is most pronounced in the subcooled condition. In fact, figure 3(c) shows that there is no vapor slug burst with water at saturated conditions. The thermocouple did sense the local periodic surface temperature fluctuations associated with the ebullition process. Thus it might be concluded that the development of the vapor slug is a necessary transitionary step to the thermal conditions for the onset of subcooled nucleate boiling. Reference 11 shows




(a) Fluid, alcohol; bulk temperature, 130° F; heat input, 0.0169 Btu per second.

(b) Fluid, alcohol; bulk temperature, 156° F; heat input, 0.01 Btu per second.

(c) Fluid, water; bulk temperature, 189° F; heat input, 0.03 Btu per second.

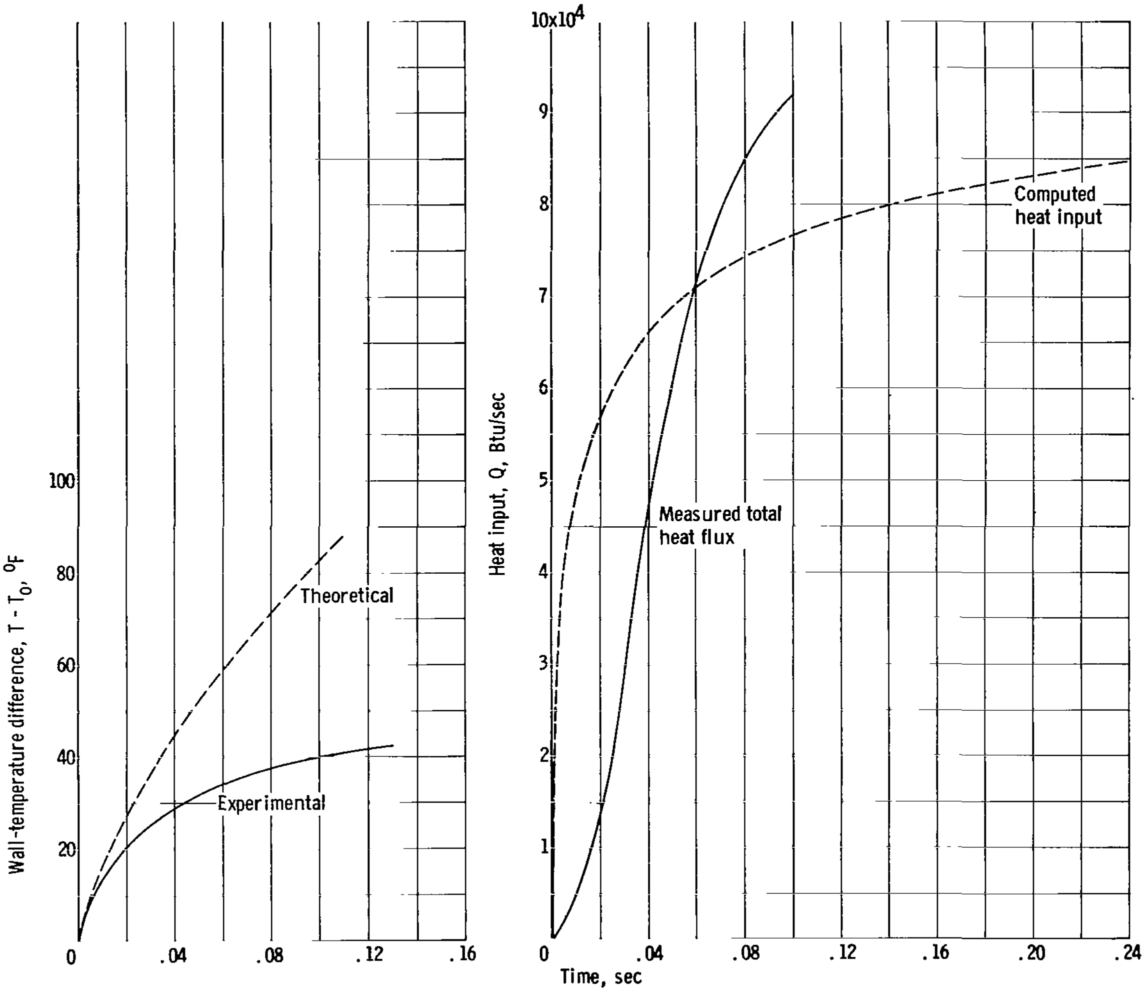
Figure 5. - Comparison of experimental wall-temperature transient with analytical prediction. Pressure, 1 atmosphere.

that a definite thermal layer profile is needed before a site will become active. Subcooled liquids require much larger driving temperatures for the initiation of boiling as compared to saturation. Thus in transient boiling, a nearly saturated liquid goes into nucleate boiling easily without a significant overshoot and undershoot. A subcooled liquid, however, permits the surface temperature to rise sufficiently to produce an explosive-like production of vapor over a large surface area.

It is desirable to know more about the details of the transient excursion that led to the events in figures 2 and 3.

It was concluded in reference 4 that the surface temperature excursion during the transient heating of a vertical ribbon could be predicted by assuming that the heat-transfer process was simply transient conduction. In the same reference the experimental data were compared to a transient conduction solution in which the fluid was treated as a semi-infinite slab. (The heat capacitance of the heater ribbon was accounted for.) Generally the predicted wall temperature was somewhat higher than the measured. The best agreement occurred at a high heat flux in a subcooled pool.

The analytical method of reference 4 was employed to compare the experimental results with the transient conduction predictions. For the convenience




(a) Wall temperature; heat input, 0.03 Btu per second.

(b) Heat fluxes; heat flux, 0.39 Btu per square inch per second.

Figure 6. - Measured and computed transient wall temperatures and heat fluxes for subcooled water; bulk temperature, 166° F. Pressure, 1 atmosphere.

of the reader, the basic equations and assumptions appear in appendix B.

The heater-ribbon geometry studied herein was a horizontal orientation of the ribbon cemented to a bakelite block. The horizontal orientation of the ribbon is an important feature to be remembered. (The heater ribbon analyzed in ref. 4 was vertically suspended with both surfaces in contact with the liquid.) The thermal capacitance of the bakelite block appeared to complicate the analysis until it was observed that bakelite has approximately the same thermal diffusivity as water. Thus it was assumed that the block and the water would absorb approximately equal amounts of heat flux.

Figures 5 and 6(a) compare the experimental temperature transients with the transient conduction predictions for alcohol and water, respectively. For all of the subcooled cases, the similarity between the experimental and pre-

TABLE I. - COMPARISON OF MEASURED AND COMPUTED TEMPERATURE AND HEAT FLUXES

[Transient conduction solution of appendix B was utilized.]

| Time, t, sec | Experimental | | | Computed | | | |
|---|---|---|---|---|---|---|---|
| | Temperature difference, $\Delta T$ | Heat flux, q | Experimental instantaneous heat-transfer coefficient, $q/\Delta T$ | Temperature difference, $\Delta T$ | Heat flux, q | Computed instantaneous heat-transfer coefficient, $q/\Delta T$ | Nusselt number, $\frac{(q/\Delta T)_{experimental}}{(q/\Delta T)_{computed}}$ |
| 0.01 | 13 | $0.5\times10^4$ | $0.038\times10^4$ | 18 | $4.7\times10^4$ | $0.26\times10^4$ | 0.146 |
| .02 | 20 | 1.3 | .65 | 28 | 5.6 | .2 | .32 |
| .03 | 26 | 3 | .11 | 36 | 6.2 | .17 | .65 |
| .04 | 30 | 4.7 | .16 | 45 | 6.6 | .14 | 1.14 |
| .05 | 33 | 6.1 | .18 | 52 | 6.9 | .13 | 1.4 |

dicted temperatures was poor; the actual wall temperatures were less than those predicted. Only in the very early stages of the transient was there any reasonable agreement between experiment and analysis. This lack of agreement indicates that the transient case for the horizontal heater differs from that of the vertical heater (ref. 4).

For the horizontal surface, a Rayleigh-Taylor instability involving mass transport to and from the heating surface could begin immediately with the transient mechanism. This suggests that the onset of this free convection mechanism in the transient should be examined.

## Transient Free Convection on a Horizontal Surface

In considering the possible introduction of free convection in the transient, several approaches will be discussed. The question is which criteria or experimental techniques can be employed to ascertain whether free convection is present.

A first approach might be to consider the transient as a series of quasi-steady conditions and to compute the instantaneous experimental heat-transfer coefficient. The ratio of this experimental coefficient to a corresponding coefficient, computed by assuming a transient conduction process, might be interpreted as a kind of Nusselt number. Whenever this Nusselt number exceeds unity, free convection is presumed to be involved. The use of this criterion is illustrated by using the data of figure 6 for subcooled water. Table I, which is based on figures 6(a) and (b), contains the measured and computed temperatures and heat fluxes.

This simple criterion indicates that free convection began in the vicinity of 0.04 second after the heat was applied. In general, a similar table of Nusselt numbers can be generated for all the runs with water and alcohol; however, the occurrence of a computed Nusselt number that exceeds unity cannot be taken as an indication of the presence of free convection. More direct experimental proof is needed.

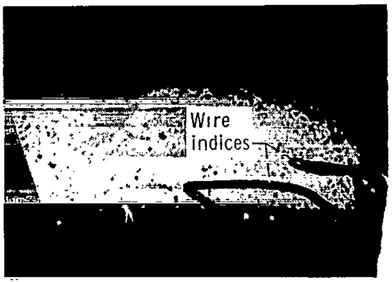
The need for more direct experimental proof led to an extension of the experimental program in which a shadowgraph optical system was employed. This program extension is referred to as phase II in the APPARATUS AND PROCEDURE section.

As is evident from a comparison of figures 1(b) and (c), the heater in phase II was smaller than the one used in phase I; the length of the heater block was different, but the width and thickness of the heater ribbon were the same. The only reason for this change in length was the physical limits of the tank used in phase II.

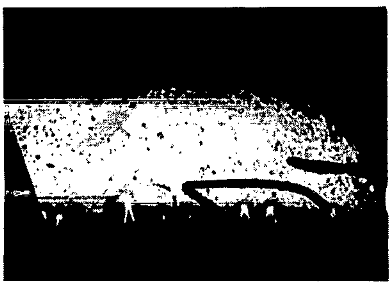
One of the early observations in this program was the presence of a convective wave prior to the appearance of boiling at the surface. Figure 7 is a series of prints of high-speed motion-picture frames, which show the convection wave developing. Nucleate boiling is just beginning on the surface. Figure 8 is another series of pictures that shows a columnar instability taking place in the thermal layer just prior to boiling. From these pictures it is evident that there is first a rapid initial buildup of the thermal layer (frames 1 and 2). Presumably this buildup is the result of thermal conduction. Soon thereafter an instability is evident by the appearance of columns, which appear to transport fluid upward from the heating surface. Finally, in frame 4, boiling is evident. This sequence of pictures is similar to those in reference 12, and the instability was improperly labeled as Bénard cells. These are not the classic Bénard cells noted in thin liquids during steady-state free convection. Their columnar and turbulent appearance make them seem more similar to the convection currents noted by Chandra (ref. 13). He noted that for thin layers, columnar rather than cellular currents developed regardless of the temperature difference.

It is suspected that this columnar instability develops within the thin thermal layer produced by thermal conduction in the initial moments of the transient.

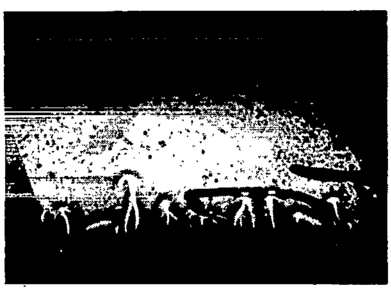
The steady-state free convection process off a horizontal flat plate was studied in reference 14. The apparatus used was considerably different from



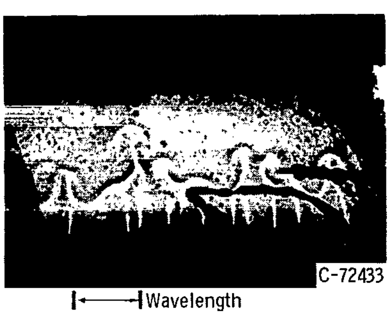

(a) Columnar instability beginning.



(b) Wave front forming (0.13 sec after beginning of columnar instability).



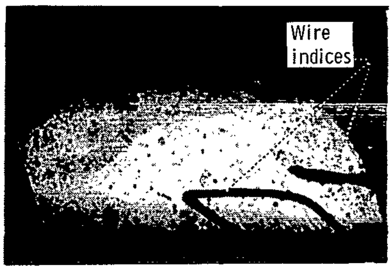
(c) Wave front leaving heater (0.28 sec after formation of wave front).




(d) Wave front showing wavelength (0.45 sec after wave front leaves heater).

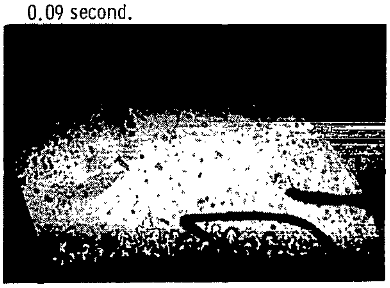
Figure 7. - Development of convection wave during heating transient for water.


(a) Isothermal condition; time, 0 second.



(b) Developed thermal layer; time, 0.02 second.


(c) Beginning of columnar instability; time, 0.09 second.


(d) Initial boiling; time, 0.13 second.

(e) Further developed boiling; time, 0.18 second.

Figure 8. - Shadowgraphs of columnar instability and ensuing boiling for water.

the flat plate used herein. A circular flat plate was used as the heating surface, and the liquid layer was relatively thin. Actually, the liquid layer thickness, which was varied from 1.45 to 12.98 millimeters, was one of the main controls of the experiment. The shadowgraph was employed to observe the free convection cells. It was definitely established, with five different liquids, that free convection begins after a critical Rayleigh number of 1700 is surpassed. The Rayleigh number is defined as

$$Ra = \frac{g\beta\Delta t\lambda^3}{8\alpha\nu} \qquad (1)$$

(Symbols are defined in appendix A.)

The wavelength $\lambda$ for a Bénard cell is defined more adequately in figure 9, which shows the vertical section of a horizontal heater. Reference 14 shows how the Rayleigh number progresses from the critical value (1700) to laminar, then to transition, and finally into turbulent convection. The latter occurs when the Rayleigh number approaches 40,000 to 50,000 and extends to Rayleigh numbers as high as $10^7$. At these high Rayleigh numbers, the convection patterns were disordered and not in the neat hexagonal cell patterns of the laminar regime. Figure 9 is not applicable to the free convection shown in figures 7 and 8.

Figure 7, which indicated the spacings for columns of rising liquid, was used to estimate the Rayleigh number. The wavelength was taken as the distance between the rising columns. A value (approximately 1/4 in.) was inserted in equation (1), and the resulting Rayleigh number was approximately 50,000. With the criteria of reference 14, this magnitude of Rayleigh number indicates that a turbulent free convection is well established.

The presence of convection columns and the realistic magnitudes of the Rayleigh numbers contribute more evidence that a convective mechanism is at work over a portion of the transient. This is why the temperature curves (figs. 5 and 6) depart from the transient conduction prediction.

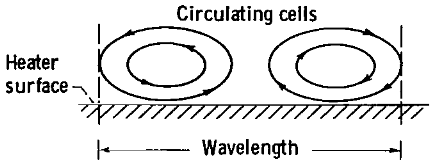


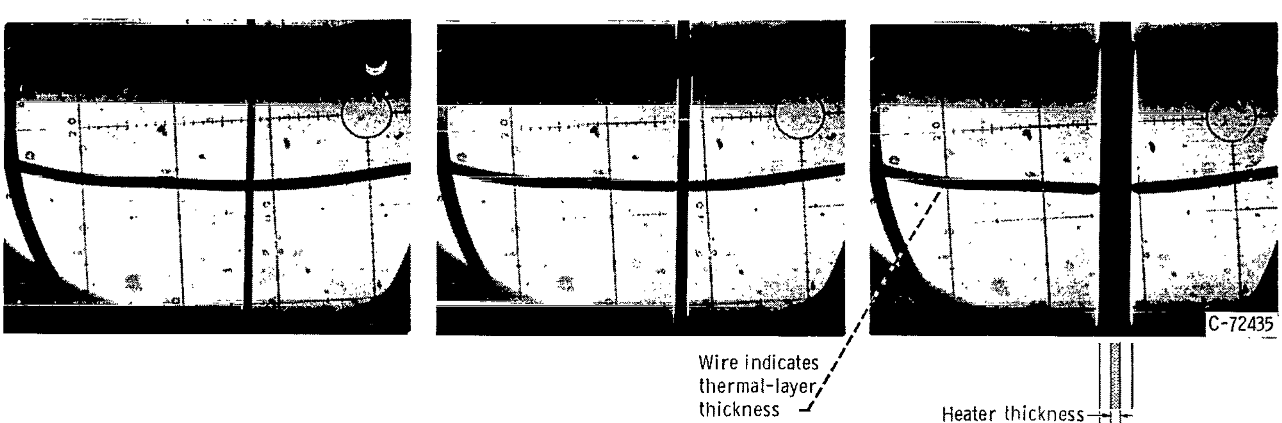
Figure 9. - Wavelength for Bernard cell.

## Boundary-Layer Growth Profiles

A further outgrowth of the shadowgraph studies of the thermal boundary layer was the measurements of the thickness history of the boundary layer. These measurements were made on a heater ribbon that was suspended between two arms of a bakelite yoke (see fig. 1(c)). The thermal-layer thickness was measured on each side of the heater ribbon for both vertical and horizontal positions. Heat flux and subcooling were additional variables in this series of experiments. Figure 10 contains three selected frames taken from a high-speed motion-picture sequence of the thermal layers on both sides of the suspended vertical heater. The arrangement of the lighting and the position of the iris of the camera actually produced a schlieren image rather than a shadowgraph image of the thermal layer. For this reason the thermal layer appears so dark.

Figure 11 is a collection of thermal-layer histories for the horizontal position, and figure 12 is a similar collection for the vertical position. There are several interesting observations to be made from these growth curves. First, it is apparent that the initial growth rate of the boundary layer is very rapid, and the subsequent growth rate tapers off continuously. The growth rate appears to be proportional to the square root of time. As would be anticipated, the growth rate is strongly dependent on the level of the heat flux; the higher the heat flux, the more rapid the boundary-layer growth.

The initiation of boiling on a surface is obvious by the wild fluctuations in the boundary-layer thickness when boiling begins. The magnitude of the plotted thermal-layer thickness has no particular meaning other than to point out that the thermal boundary layer is highly disturbed during boiling. The surface location, where the boundary layer thickness was measured, was chosen arbitrarily. In the vicinity of a nucleation site, the boundary layer thickness was a function of both space and time (ref. 15). The selection of another surface location would show a different distribution of thickness against

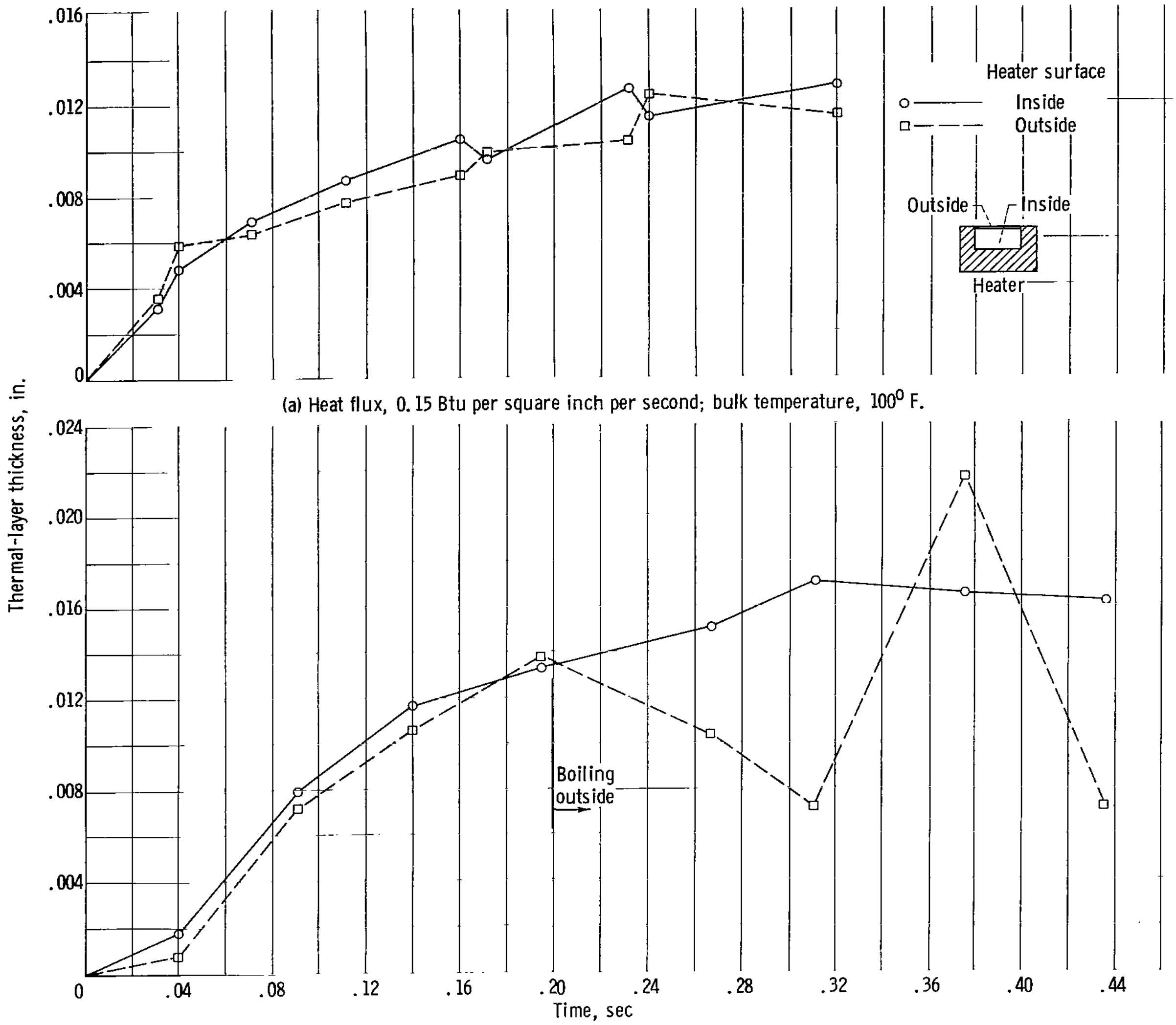


(a) No heating.

(b) During transient.

(c) Steady free convection. Growth of thermal layer by transient heating; run 39.

Figure 10. - Shadowgraph images of thermal-layer growth on vertical ribbon. (Note: reticle graduation.)



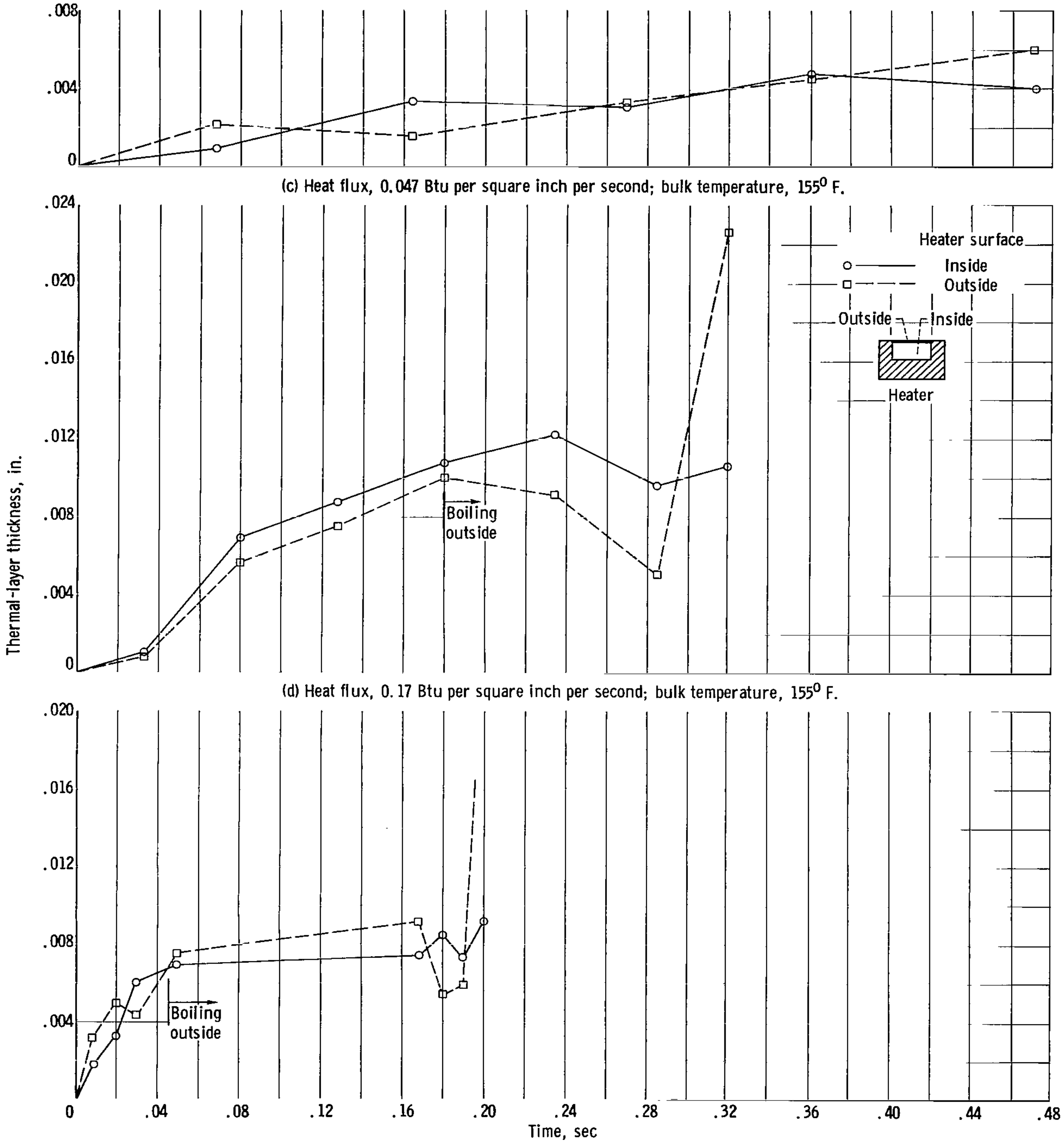

(b) Heat flux, 0.33 Btu per square inch per second; bulk temperature, 100° F.

Figure 11. - Thermal-layer-thickness histories of water for horizontal position. Pressure, 1 atmosphere.

time, but it would still indicate a wildly fluctuating boundary layer during the boiling cycle.

Figure 13 utilizes some of the data from figures 11 and 12 to illustrate that the boundary-layer thickness just prior to boiling must be greater as the subcooling increases. Intuitively, this statement makes sense because it does seem reasonable to expect that the thermal layer would have to be thicker to satisfy superheat conditions in a sublayer adjacent to the wall that accommodates a growing bubble (ref. 11).

It is also apparent that the absolute magnitude of the thickness depends on the surface being considered and the horizontal or vertical position of the heater ribbon. A thermal-layer thickness for a low velocity flow of water taken from reference 15 is shown in figure 13. The magnitudes seem comparable.




(e) Heat flux, 0.37 Btu per square inch per second; bulk temperature, 155° F.

Figure 11. - Concluded. Thermal-layer-thickness histories of water for horizontal position. Pressure, 1 atmosphere.

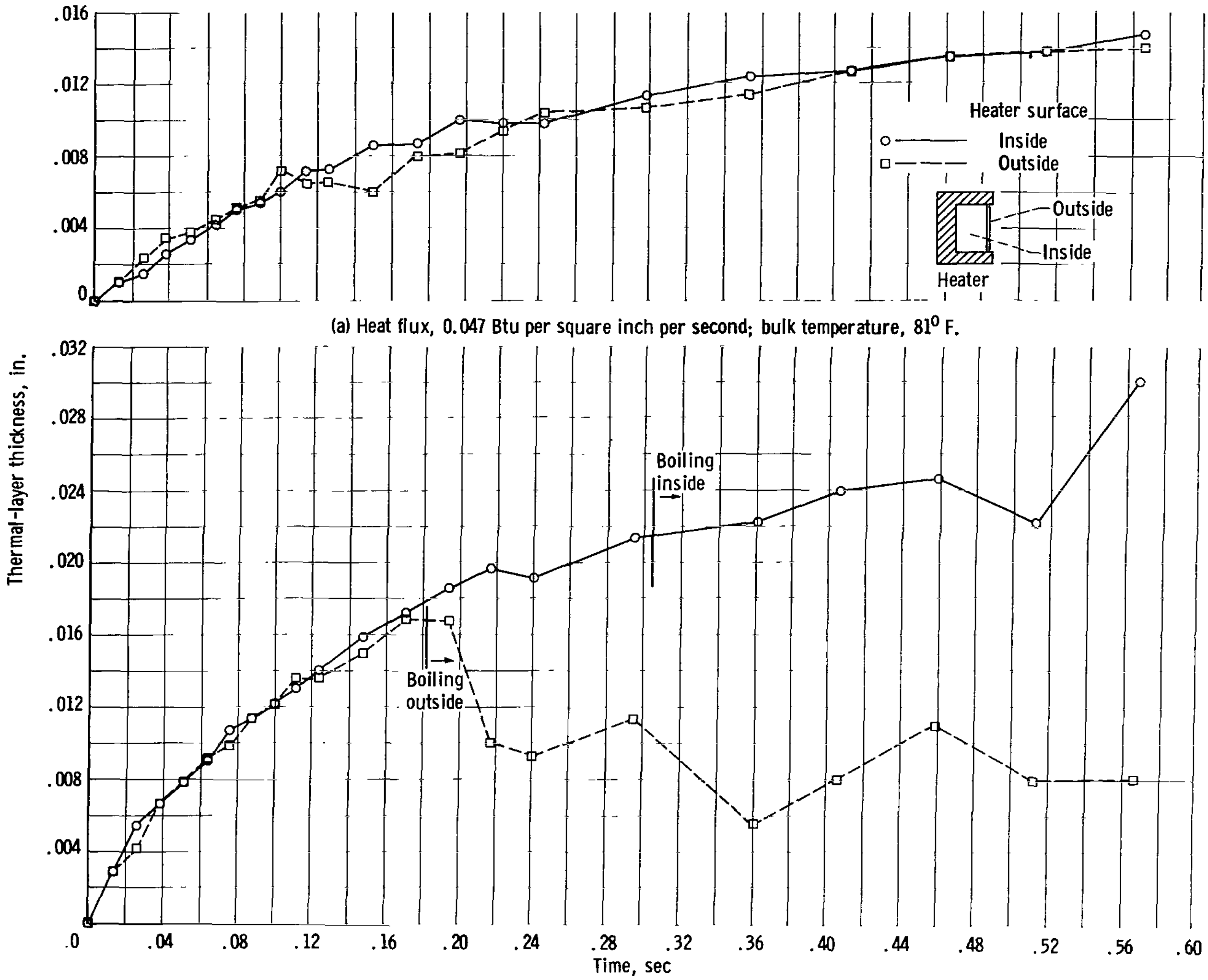



Figure 12. - Thermal-layer-thickness histories of water for vertical position. Pressure, 1 atmosphere.

It was observed that for both orientations, vertical and horizontal, one side of the suspended ribbon was more active during boiling than the other. This tendency is indicated in the boundary-layer measurements of figures 11 and 12 where boiling develops on one of the surfaces before it develops on the other. The surface that faced the base of the heater yoke (see fig. 1(c)) was less active than the other surface. To eliminate the possibility of heater-geometry effects, the heater strip was remounted with the surfaces reversed in orientation to the heater yoke. The boiling transient was then observed with this orientation. Figure 14 contains prints of selected motion-picture frames for the suspended heater ribbon in both orientations, which verified that the surface condition alone was accountable for the asymmetry of the boiling. The heater was in the vertical position so that the gravity effects were equal on each surface. The effect of surface condition on steady-state boiling activity has been observed by many investigators. These results verify that similar behavior is observed in transient boiling.

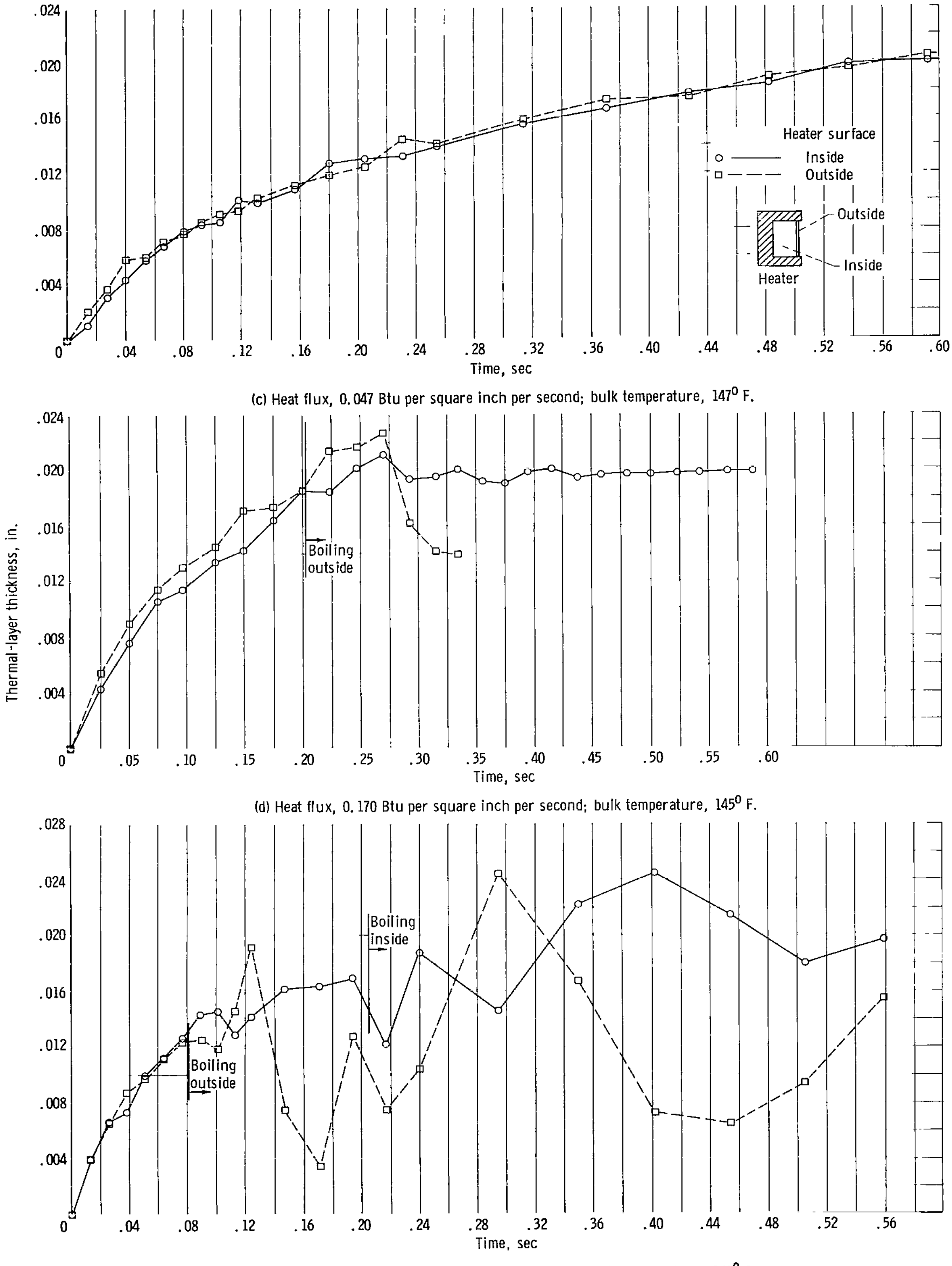



Figure 12. - Concluded. Thermal-layer-thickness histories of water for vertical position. Pressure, 1 atmosphere.

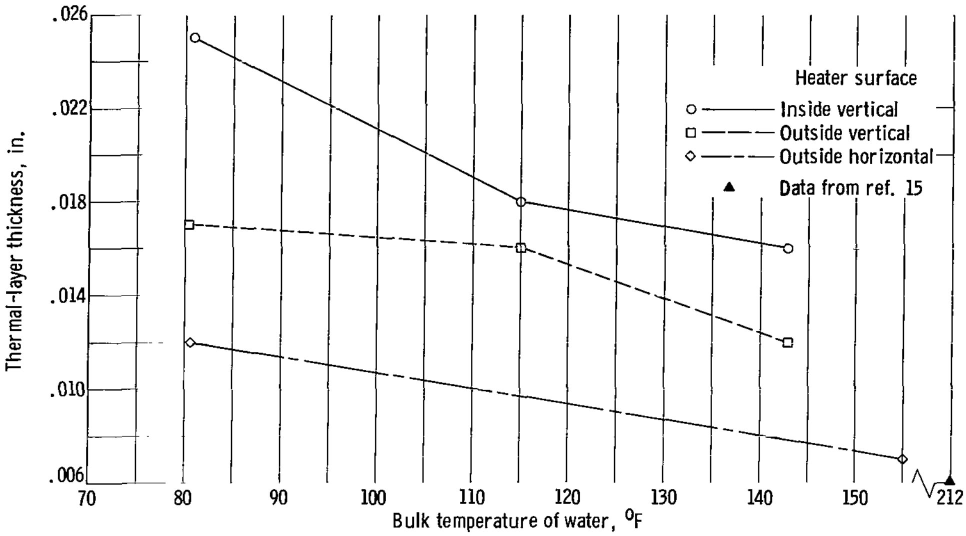
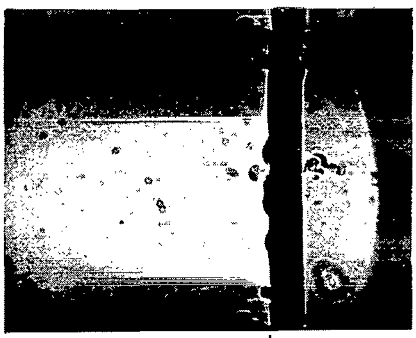
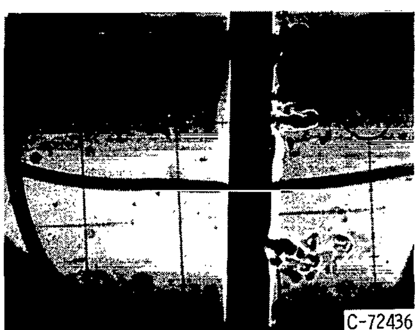



Figure 13. - Influence of bulk temperature on thermal-layer thickness at boiling for water. Heat flux, 0.37 Btu per square inch per second. Pressure, 1 atmosphere.




(a) Beginning of boiling in transient. Active surface to the left; run 65.




(b) Steady boiling at low heat flux. Active surface to the right; run 43.

Figure 14. - Comparative shadowgraphs of boiling from suspended ribbon showing influence of surface condition.

## Hysteresis Effects

These transient studies do show the importance of thermal-layer history in determining the boiling conditions. Figures 11 and 12 have shown that the boundary-layer growth rate is dependent on the magnitude of the heat flux. In the discussion of figures 2 and 3, it was pointed out that an overshoot and an undershoot in wall temperature occurred in the transient before steady nucleate boiling was established. Particularly with alcohol, a pronounced vapor burst was observed before established nucleate boiling developed. When a steady-state boiling curve is used, the transient can be imagined as being similar to the dashed line in figure 15.

Hysteresis effects in establishing steady-state nucleate boiling points were noted in reference 5. If it is possible to think of the transient as a series of quasi-steady points, then the transient illustrates that a complex history of the thermal layer is possible. Even if an operating point is approached slowly, certain transitions must be effected as the steady-state point is approached. The rapid transients of this investigation may exaggerate the thermal-layer transitions in the steady-state situation, but they do indicate that several heat-transfer mechanisms can exist at a given heat flux, that is

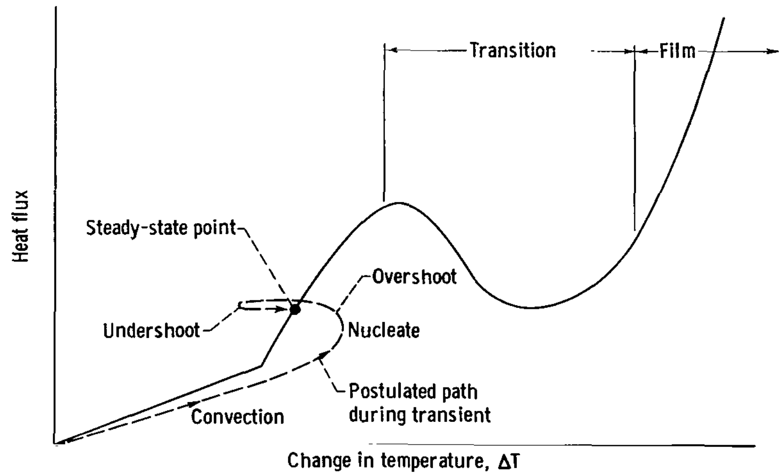



Figure 15. - Schematic of transient.

time-dependent. In addition, experimental studies that involve transient techniques to gain steady-state boiling or burnout information must be questioned.

## Gravitational Effects

Certainly the onset of the columnar instability noted in figures 7 and 8 is a gravitational effect. The body force is directed such that mass transport takes place normal to the horizontal surface, thus conduction is not the only heat-transport mechanism in the transient. Such a mass-transport mechanism is not possible with a vertical heater during the transient. The body force does produce fluid motion, and indeed it eventually produces a convective velocity profile; however, the development requires a finite time greater than the transient times experienced herein to establish itself over the entire surface height. The preceding was demonstrated by the interferometer studies in reference 17. Thus the differences between the transient heating curves for horizontal- and vertical-surface results are attributed to the orientation of the body force with respect to the heating surface. (See the section Transient Free Convection on a Horizontal Surface.)

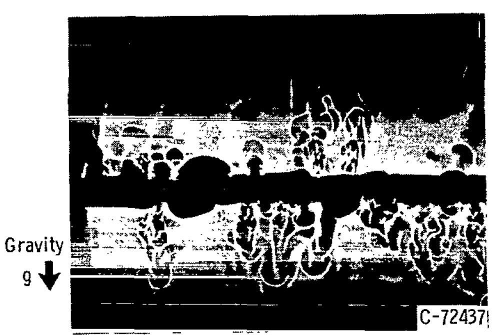



Figure 16. - Shadowgraph of boiling on both sides of suspended horizontal ribbon illustrates absense of gravitational influence.

A further interesting observation of the transient boiling behavior was the relative independence of the subcooled-boiling ebullition characteristics to the gravitational vector direction. Figure 16 shows a shadowgraph image of boiling on the horizontal heater ribbon. The most active boiling surface is facing downward. From the thermal patterns displayed in figure 16, it is apparent that the bubbles penetrate as far from the bottom surface as they do from the top surface. Some estimates of the bubble velocities for both surfaces were made from the high-speed motion pictures, and it is surprising that the bubble velocities were relatively insensitive to the body force. Also, it was noted that the bubble trajectories from the vertical heater were straight and normal to the surface. Consequently, the absence of the body-force influence on the ebullition characteristics for each orientation led to the conclusion that the inertia effects outweigh any body-force effects in subcooled boiling.

## SUMMARY OF RESULTS

Observations of transient boiling of subcooled water and alcohol on a horizontal surface led to the following:

1. The stepwise transient up to the boiling condition is not a conduction process only; free convection can be significant. This differs from the observation using a vertical heater.

2. The Rayleigh criteria for a turbulent-type free convection appear applicable to the transient situation. The observed wavelength between adjacent rising columns was inserted in the Rayleigh number and indicated that free convection must be active.

3. The so-called undershoot of temperature in the region of boiling inception is attributed to evaporation and not to liquid quenching.

4. For the suspended ribbon, the growth rates and thicknesses of the thermal layer on each side of the ribbon are similar during the early portion of the transient. This is true whether the ribbon is mounted horizontally or vertically and is indicative of a thermal conductance mechanism. As the boiling condition is approached, the thicknesses on opposite sides of the horizontal heater become dissimilar, which indicates convection effects.

5. The thermal boundary-layer growth curve appears to be a square root function of time. The growth is rapid at the beginning and then maximizes fairly slowly.

6. As would be expected, the maximum boundary-layer thickness is an inverse function of bulk temperature.

7. Thermal-layer thickness alone is not a sufficient criterion for determining the onset of boiling. Surface condition is a first-order effect.

8. The thermal trajectories of bubbles in subcooled boiling are relatively independent of gravity for appreciable distances out from the heater surface.

9. These transient studies have illustrated how several boiling modes are achievable at one heat flux. The thermal-layer history is a dominant influence. This may explain the hysteresis phenomena noted in nucleate boiling experiments. Transient boiling or burnout data cannot generally be interpreted as being typical of the steady-state counterparts.

10. Within the limits of the conditions of these experiments, the series of mechanisms associated with transient boiling seem to act as restraints on any excursion into a high wall-temperature condition.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 4, 1964.

# APPENDIX A

## SYMBOLS

$C_p$ specific heat

$c$ thermal capacity of metal

$g$ local gravity, ft/sec$^2$

$H$ thermal capacity of ribbon per unit surface area, $1/2\ \rho_m c_m \delta$

$k$ thermal conductivity

$q$ heat flux

$q_o$ steady-state power input

Ra Rayleigh number

$T$ ribbon surface temperature

$T_o$ steady-state ribbon surface temperature

$t$ time

$\Delta t$ change in time

$\alpha$ thermal diffusivity

$\alpha_f$ $k/(\rho C_p)_f$

$\beta$ coefficient of volumetric

$\delta$ thickness of ribbon

$\lambda$ wavelength

$\mu$ $(kt/H)\sqrt{t/\alpha_f}$

$\nu$ kinematic viscosity, $\mu/\rho$

$\rho$ density

Subscripts:

f fluid

m metal ribbon

t time

## APPENDIX B

## APPROXIMATE SOLUTION OF TRANSIENT HEAT TRANSFER

## FROM HOT RIBBON TO FLUID

The transient heat transfer from a ribbon that is cemented to a bakelite block and is exposed to a liquid on the free surface (fig. 17) can be approximated. When transient conduction is the prevalent mechanism, the thermal diffusivity of water and alcohol are approximately equal to that of bakelite. Thus, it is assumed that equal parts of the generated flux are divided between the block and the liquid. With this assumption, the solution to a one-dimensional transient conduction solution would correspond to the solution presented in reference 4.

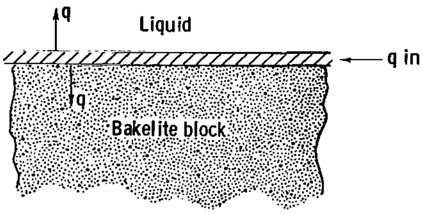



Figure 17. - Transient heat transfer from ribbon cemented to bakelite block and exposed to liquid on free surface.

The heat flux equation is

$$q = q_o(1 - e^{\mu^2}\operatorname{erfc}\mu) \qquad \text{(B1)}$$

The surface temperature, written in terms of a temperature difference, is

$$T - T_o = q_o \frac{\alpha_f H}{k_f}\left[\frac{2\mu}{\sqrt{\pi}} - (1 - e^{\mu^2}\operatorname{erfc}\mu)\right] \qquad \text{(B2)}$$

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